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Evidence for subaerial development of the Caribbean oceanic plateau in the Late Cretaceous and palaeo-environmental implications

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ABSTRACT

The formation of oceanic plateaus in the Pacific in the Mesozoic has been proposed to create major environmental impacts, including global anoxic events OAE-1 in the Aptian (ca. 120 Ma) and OAE-2 in the Cenomanian–Turonian (ca. 90 Ma). However, our understanding of the formation of these large volcanic systems and their environmental effects are strongly limited by difficulties in accessing them and characterising their volcanic evolution. In particular, it remains significant to determine whether Pacific oceanic plateaus experience a phase of subaerial volcanic activity as this has critical implications in terms of their environmental impacts. Herein we provide the first unequivocal evidence for an emergent volcanic phase of the Caribbean oceanic plateau in the Late Cretaceous. This subaerial phase is evidenced by accreted oceanic sequences in Colombia that include fallout tuffs with accretionary lapilli and lahar deposits. This facies assemblage, recognised for the first time in an oceanic plateau, reflects phreatomagmatic eruptions coeval with subaerial erosion on an oceanic island. This result, combined with previous evidence of subaerial development of the Ontong Java Plateau and Shatsky Rise, suggests that syn-volcanic emergence of oceanic plateaus was common in the Pacific during the Mesozoic. Although temporal and spatial scales of these emergences remain poorly constrained it confirms that emergence of the Caribbean plateau in the Late Cretaceous (ca. 90 Ma) could have actively contributed to atmospheric changes and the establishment of OAE-2. Significantly, emergence of the Caribbean plateau occurred synchronously to the beginning of its tectonic displacement between the Americas. We propose that this unusual volcanic and tectonic evolution led to drastic reduction of the flow of Pacific oxygenated bottom waters into the early Atlantic basin, leading to a series of regional anoxic events previously documented between the Coniacian and Santonian (OAE-3, ca. 89 to 84 Ma). In addition, emergence of the Caribbean Plateau in the early inter-American seaway could have facilitated migration of terrestrial organisms between the Americas in the Late Cretaceous. The formation of the Caribbean plateau had therefore a large range of possible environmental effects, from atmospheric to palaeo-oceanographic and biotic impacts.

1. Introduction

Oceanic plateaus are a type of large igneous province that develop in the oceans and represent some of the largest volcanic systems on Earth. The formation of oceanic plateaus in the Pacific Ocean during the Cretaceous (i.e., Ontong Java, Manihiki, Hikurangi, Caribbean, Shatsky Rise and Hess Rise) was associated with rapid release of large volumes of magmatic gases and volcanic nutrients that could have triggered global oceanic anoxia and mass extinctions (Sinton and Duncan, 1997; Kerr, 1998; Kuroda et al., 2007; Yasuhara et al., 2017). If these oceanic plateaus experienced a phase of subaerial volcanism, their formation could have more severely affected the atmosphere, with significant implications for the nature and extent of their global environmental impact (e.g., Kuroda et al., 2007).

Cretaceous oceanic plateaus in the Pacific have a considerable crustal thickness of approximately 10 to 30 km (e.g., Eldhom and Coffin, 2000), but evidence for their emergence remain very limited, relative to their large surface area (i.e., typically of the order of 1×10^6 km^2). Wood fragments, shallow-marine sediments and

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subaerial fallout tuff with accretionary lapilli have been locally described in drill cores from the Ontong Java Plateau (Thordarson, 2004) and Shatsky Rise (Yasuhara et al., 2017). However, these occurrences lack thick coastal to subaerial deposits commonly observed in the geological record of modern and ancient Pacific oceanic islands (Garcia et al., 2007; Buchs et al., 2011, 2018). Some uplifted sections of the Caribbean plateau on Aruba Island and in the Western Cordillera of Colombia suggest that this volcanic edifice could have developed partly subaerially in the Cretaceous (White et al., 1999; Moreno-Sanchez and Pardo-Trujillo, 2003; Kerr, 2014). However, observations from these areas are ambiguous due to their complex geological settings and lack of detailed lithological and geochemical constraints. Overall, a limited record of subaerial activity on top of Pacific oceanic plateaus may reflect a fundamental characteristic of these volcanic edifices, but it could also be an observational bias due to logistical difficulties in conducting subsurface observation and sampling of very large, deep marine volcanic sequences.

In this paper we present new field observations and geochemical data from volcanic sequences of the Caribbean plateau that formed in the Pacific in the Cretaceous and were subsequently accreted and exposed along the northern margin of South America in Colombia (Fig. 1). These sequences offer a unique access to the main volcanic phase of the plateau, before renewed volcanism associated with the inter-American evolution of the Caribbean Large Igneous Province. Notably, these sequences preserve volcaniclastic deposits not recognised before on top of Pacific oceanic plateaus, and so provide novel and compelling evidence for subaerial development of the Caribbean plateau. We show that this development was associated with a specific palaeogeographic context that could have triggered anoxic events in the early Atlantic basin from the Coniacian to Santonian (OAE-3, ca. 89 to 84 Ma, Wagreich, 2012), and could have facilitated inter-American exchange of terrestrial organisms in the Late Cretaceous.

2. Geological background

The studied oceanic sequences are exposed in the Western Cordillera of Colombia approximately 30 km west of Medellin close to Altamira village on the western side of the Cauca valley (Fig. 1). The sequences include tuffs with accretionary lapilli recently interpreted to be part of an accreted fragment of the Caribbean plateau (Zapata-Villada et al., 2017). However, this work did not undertake a detailed characterisation of the origin and implications of these sequences for the volcanic evolution of the plateau. The tuffs occur in a complex area comprising imbricated, fault-bounded igneous and sedimentary units west of the Cauca fault. This fault marks a significant boundary with the Quebradagrande Complex to the east, which formed in an extensional, supra-subduction continental margin setting in the Early Cretaceous (Bourgois et al., 1987; Nivia et al., 2006; Villagómez and Spikings, 2013; Spikings et al., 2015; Jaramillo et al., 2017). Eastward migration of the Caribbean plateau between the Americas in the Late Cretaceous led to tectonic inversion of this margin and accretion of units in the region that now comprises the Western Cordillera (Kennan and Pindell, 2009). The accreted units are generally considered to be composed of igneous rocks of the Caribbean plateau (Barroso formation, *sensu* Kerr et al., 1997 and Villagómez et al., 2011) and its Upper Cretaceous pelagic to near-trench sedimentary cover (Penderisco formation) (Kerr et al., 1997; Moreno-Sanchez and Pardo-Trujillo, 2003; Villagómez et al., 2011). The igneous sequences consist of massive and pillowed basalts with dolerites and subordinate gabbroid intrusions that have oceanic plateau geochemical affinities and Ar–Ar and U–Pb zircon ages of approximately 100 to 91 Ma (Kerr et al., 1997, 2004; Villagómez et al., 2011). Similar sequences with plateau affinities occur in the studied area, including a gabbro dated at 89.9 ± 1.5 Ma (U–Pb zircon age, Zapata-Villada et al., 2017).

It has been suggested that possible coral remains found in tuffs from the Antioquia area (Hall et al., 1972) and sedimentary rocks including colonial corals and conglomerate with carbonized fragments of tree trunks in the Belen de Umbría region (Moreno-Sanchez and Pardo-Trujillo, 2003) could reflect subaerial volcanic activity of the Caribbean plateau exposed in the Western Cordillera (Moreno-Sanchez and Pardo-Trujillo, 2003; Kerr, 2014). However, the sedimentary rocks in the Belen de Umbría region contain detrital quartz of possible terrigenous origin and have been dated to the Campanian–Maastrichtian based on ammonite fossils (Moreno-Sanchez and Pardo-Trujillo, 2003); these clearly postdate published ages of Caribbean plateau volcanism in the Western Cordillera. In addition, recent studies reveal that the northern Western Cordillera also includes Lower Cretaceous arc-related units, which crosscut or are tectonically (?) intercalated with Caribbean plateau sequences (Rodríguez and Arango, 2013; Weber et al., 2015). This makes the interpretation of the origin of tuffs reported by Hall et al. (1972) and parts of the Barroso formation uncertain, in particular where detailed field observations and geochemical constraints are lacking. This also questions the validity of previous regional tectonic and palaeogeographic reconstructions. The tuff locality that is the focus of the present study therefore provides a rare and valuable opportunity to test and characterise subaerial volcanic activity associated with the formation of the Caribbean plateau. The age of this activity ca. 90 Ma is constrained by geochronological data in the western Cordillera (Villagómez et al., 2011; Rodríguez and Arango, 2013; Zapata-Villada et al., 2017) that are consistent with a main magmatic pulse of the Caribbean plateau ca. 90 Ma (e.g., Hoernle et al., 2004), as well as tectono-stratigraphic relationships and geochemical similarities of the volcaniclastic deposits with the dated sequences (see below).

3. Methods

In order to test a plateau origin and characterise volcanic processes associated with the emplacement of volcaniclastic deposits in the studied area, we used a field-based lithological, petrographic and geochemical approach building upon regional work by Zapata-Villada et al. (2017) and the Geological Survey of Colombia (e.g., Rodríguez and Arango, 2013). We carried out detailed observations and sampling along a track to Altamira village that is accessible from Santa Fé and offers good road cut exposures perpendicular to the strike of the bedding (Fig. 1B). Geochemical analysis of whole rock samples and clinopyroxene was used to assess the geochemical affinity of subaerial sequences, including several populations of clasts in primary and secondary volcaniclastic deposits. GPS coordinates of our samples are reported in Table S1.

Analysis of major and trace elements of 19 whole rock samples was conducted at Stellenbosch University (Table S2, including analysis of certified samples). Fusion disks were prepared for XRF and LA-ICP-MS analysis by an automatic Claisse M4 Gas Fusion instrument and ultrapure Claisse Flux, using a ratio of 1:10 sample:flux. Major elements were measured by XRF (Rh Tube, 3 kW). A Resolution 193 nm Excimer laser from ASI connected to an Agilent 7700 ICP-MS was used for the analysis of trace elements. Ablation was carried out in He gas at a flow rate of 0.35 L/min, then mixed with argon (0.9 L/min) and Nitrogen (0.004 L/min) just before introduction into the ICP plasma. Three spots of 228 μm were ablated on each sample using a frequency of 10 Hz and fluence of ∼5 J/cm^2, and later averaged to produce the final results. Trace elements were quantified using NIST 612 for calibration and SiO_2 from XRF measurements as internal standard. The calibration

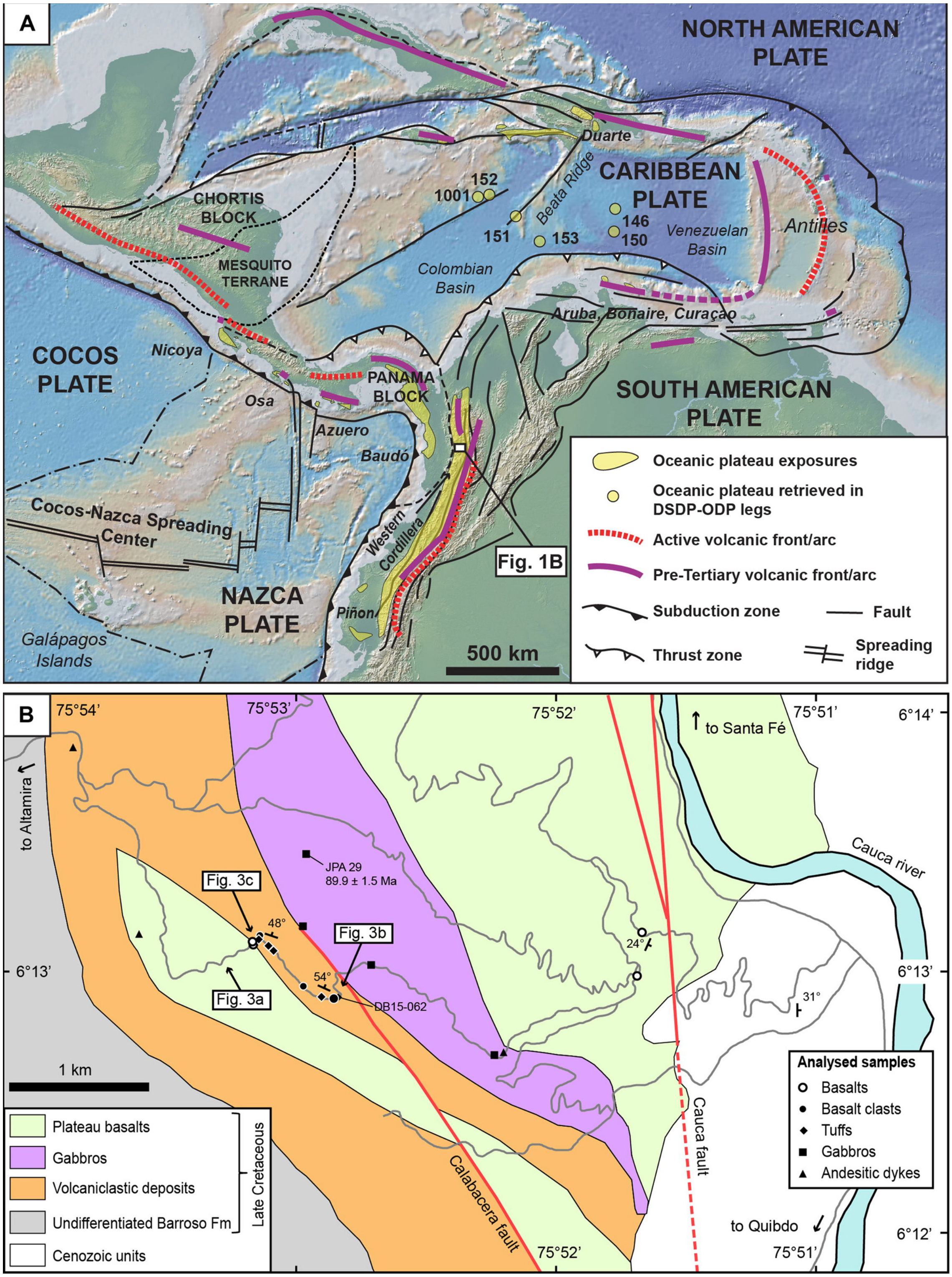

Fig. 1. Geological setting. **A)** Tectonic outline of the Caribbean Plate with main occurrences of the Caribbean Large Igneous Province (modified from Buchs et al., 2010). **B)** Simplified geological map of the studied area with location of analysed samples (same symbols as in Figs. 5–6).

standard was run every 12 samples. Data processing was carried out using the LA-ICP-MS data reduction software package Iolite v.3.2 (Paton et al., 2011). Analysis of BHVO-1 certified standard and a replicate of one of our samples were used as quality control (Table S2). RSD determined based on certified standards and repeated ablation of our samples is <5% for all trace elements used in this study. All major elements were recalculated on an anhydrous basis for interpretations.

Previous geochemical results from oceanic plateau and volcanic arc igneous rocks from the Western Cordillera (basalts to andesites including intrusive equivalents) were compiled from Kerr et al. (1997), Villagómez et al. (2011), Rodríguez and Arango (2013) and Zapata-Villada et al. (2017), with further selection of data of direct relevance to this study. Results not used here include REE, Th and Hf from Kerr et al. (1997) due to difficulty to assess whether these data compare well with those obtained by more recent analytical techniques. We did not use basalts DV75 and DV105 in Villagómez et al. (2011) that seem to have unusual, enriched trace element signatures and cannot be reliably related to the geological context of our study. Volcaniclastic samples JPA-06, JPA-26-MAS and JPA-26-FRAG in Zapata-Villada et al. (2017) were not considered due to their unclear lithological nature and relation to the studied tuff sequences. Gabbro JJ-1649 in Zapata-Villada et al. (2017) and igneous rocks from Weber et al. (2015) display chemical characteristics generally associated with mineral accumulation and therefore these samples were not used in this study. We only selected samples from Rodríguez and Arango (2013) that have unequivocal plateau and volcanic arc geochemical affinities. From our results we did not consider tuff sample DB15-069 that has very high loss on ignition (LOI = 20.66 wt.%) and unusual trace element patterns most likely reflecting post-crystallisation elemental mobility (Fig. S1).

Chemical microanalysis of clinopyroxene from 5 of our samples was carried out using a Zeiss Sigma HD Analytical Scanning Electron Microscope at Cardiff University equipped with dual 150 mm^2 active area EDS detectors and Oxford Instruments Aztec software. A beam energy of 20 kV was used with a nominal beam current of ~1 nA. The analyses were fully standardised with elements calibrated using mineral standards from Astimex Standards Ltd and Smithsonian Microbeam Standards. Accuracy and precision was measured using repeated analysis of labradorite plagioclase, chrome diopside and augite. Plagioclase analyses were performed by scanning the beam over a 10 μm area to minimise Na migration; spot analyses were used for pyroxenes. Beam drift was measured every 15 min using Co as a reference standard. SEM results and the results of standards analysed during the course of this study are given in Table S3. The analysis of standards show that elements in pyroxenes similar to those encountered in this study have a relative error generally <10%, specifically of ~1% for Ca, ~9% for Na, ~21% for Ti, and up to 30% for Cr (close to its detection limit of ~0.10 wt.%). Thus, SEM analytical error is significantly lower than the natural variability of our samples.

4. Results

4.1. Lithostratigraphy

The studied area includes four main mappable units preserved in the zeolite to prehnite-pumpellyite metamorphic facies, with from east to west: (1) a basalt unit composed of pillow lavas, massive lava flows and sills/dykes; (2) a gabbro unit; (3) a reddened volcaniclastic unit; and (4) a kilometre-sized lens of basalt unit lithologically similar to 1 above (Figs. 1B and 2). Rare cross-cutting andesitic dykes were observed in all lithologies. Bedding in the sequences dips moderately towards the E to NE. NW–SE striking faults are abundant in all sequences and form the contacts between the units (only mappable faults are shown on our Fig. 1B). These field relations are similar in most of the western flank of the Western Cordillera and confirm that the studied area is composed of an imbricated succession of accreted oceanic units. It is, however, remarkable that most of the sequences are internally poorly deformed, and so this provides a valuable opportunity to characterise volcanological processes associated with their formation.

Pillow lavas commonly found in the basalt units are a clear indication of submarine volcanic activity (Figs. 3A). Hyaloclastite, basalt breccia, and large (>5 mm) amygdales have not been encountered in these units, which suggests development in relatively deep marine conditions with a smooth volcanic topography (Furnes and Fridleifsson, 1979; Skilling, 2002). The lithology of these units contrasts with that of the volcaniclastic unit that chiefly consists of altered, red-oxidised layered tuff with interbedded layers of volcaniclastic breccia.

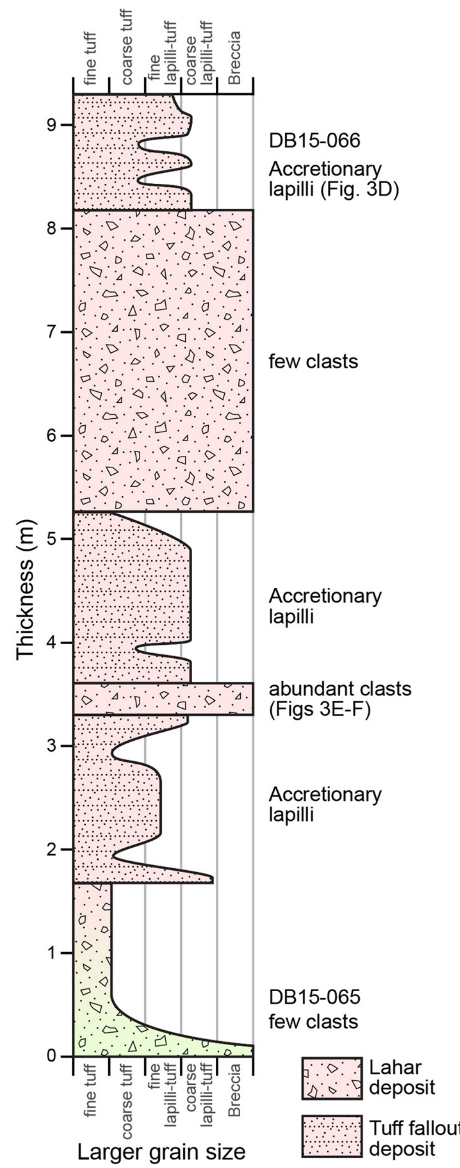

Fig. 2. Field log of a typical section of the volcaniclastic unit (also illustrated in Fig. 3C). Grain size subdivision after White and Houghton (2006).

Most of the sequences in the volcaniclastic unit include coarse reddish (more rarely green) tuff with abundant accretionary lapilli (some up to 1 cm in diameter) (Figs. 3C–D and 4). These deposits are typically well bedded/layered and graded (Figs. 2–4). The tuff generally includes rare broken crystals of plagioclase and clinopyroxene. Some layers contain armoured lapilli with a minor fraction of fragments of aphyric basalt and altered glass (Fig. 4A). Although some of the original structures in the tuffs are locally affected by alteration (Fig. 4C), no evidence for post-depositional reworking was found (e.g., broken lapilli, burrowing and lenticular bedding). Elongation of accretionary lapilli is oblique to the orientation of the bedding and is consistent with minor deformation of the accreted sequences (Fig. 4B). Beds of finer tuff, that lacks accretionary lapilli, can locally occur and form several metre-thick intervals in the volcaniclastic unit (Fig. 3B). Accretionary and armoured lapilli are only known to form due to amalgamation of ash and other fine tephra in subaerial eruption columns in response to hydro-bonds and electrostatic forces (Brown et al., 2012). Therefore, preceding observations, combined with a lack of marine microfossils and the nature of interbedded volcaniclastic breccia (see below) support a subaerial fallout origin of the layered tuffs. Red colouration of most

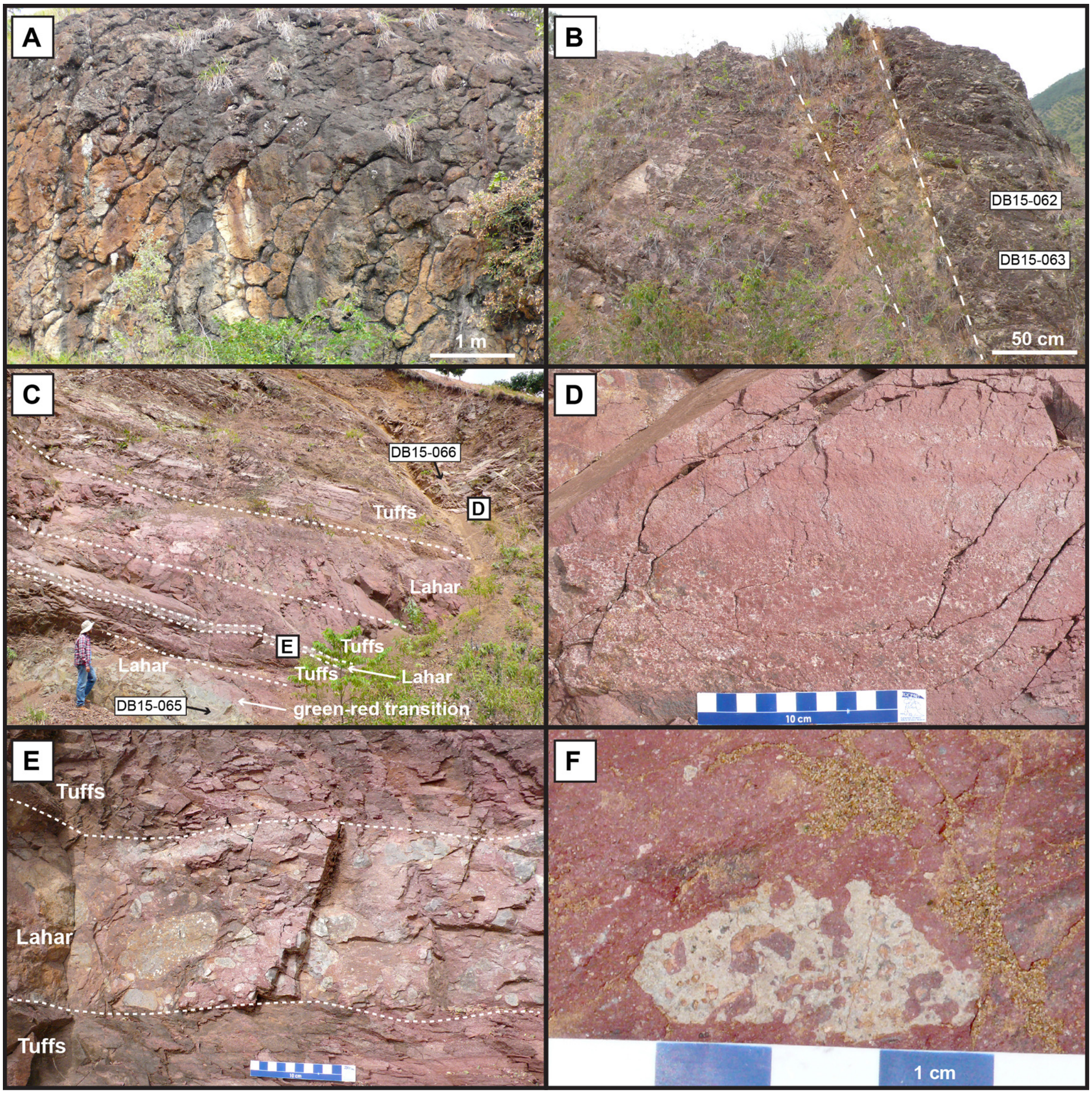

Fig. 3. Field relations and lithologies. **A)** Lobate and pillowed lavas from the basalt unit (WGS84 coordinate −75.89179/6.21727). **B)** Faulted sequence of layered ash tuff in the pyroclastic unit (WGS84 coordinate −75.88084/6.21511); this locality includes plateau-related tuff DB15-063 and arc-related tuff DB15-062 that were clearly interbedded in the field. **C)** Intercalated lahar and ash to lapilli fallout deposits with abundant accretionary lapilli in the pyroclastic unit (WGS84 coordinate −75.88191/6.21514); this locality includes green tuff DB15-065 from the matrix of a lahar deposit and lapilli tuff DB15-066 with accretionary lapilli (Fig. 4A). **D)** Layered tuffs with accretionary lapilli from the upper part of (C). **E)** Thin lahar deposit including well rounded amygdalar basalt cobbles from the lower part of (C). **F)** Juvenile (amoeboid) basalt clast from a lahar deposit in (C). (For interpretation of the colours in the figure(s), the reader is referred to the web version of this article.)

of the tuff (but not the basalt in juxtaposed units) is also consistent with subaerial oxidation of most of the volcaniclastic unit.

Layered tuff deposits are ubiquitously interbedded with tabular reddish to greenish beds of matrix-supported volcaniclastic breccia that vary in thickness between 30 cm and 5 m, and locally compose up to 40% of the volcaniclastic unit (Figs. 2B, 3C). The breccia consists of very fine to fine tuff matrix with clasts predominantly composed of basalt with large (cm-sized) amygdales (Fig. 3E). The breccia also includes few rare juvenile clasts of vesicular basalt with an amoeboid shape (Fig. 3F), but no hyaloclastite or water-quenched deposits were observed. The amount of clasts greatly varies within, and among, distinct beds (0–40%), with grading that is either normal or absent. The clasts are angular to well rounded, very poorly sorted, and range in size from a few mm to 1 m. Significantly, a large fraction of the basalt clasts are well rounded, especially in the largest cobble size range, with post-volcanic fluvial/coastal abrasion demonstrated by truncated amygdales (Fig. 3E). Preceding observations clearly indicate reworking and mixing of tuff and basalt clasts in cohesive to non-cohesive debris flows, with sedimentological characteristics similar to those of unchannelized lahar deposits in modern subaerial environments (e.g., Smith and Lowe, 1991). To our knowledge this type of deposit has not been observed before on top of an oceanic plateau.

4.2. Whole rock geochemistry

Whole rock geochemical analysis was carried out on a selection of samples from each unit to help identify their origin and possible relations prior to accretion. Following rock types were analysed and combined with previous results of Zapata-Villada et al. (2017): (1) ophitic to subophitic basalts from the basalt units; (2) fine to coarse tuffs from the layered tuff and matrix of lahar deposits in the volcaniclastic unit; (3) clasts of subophitic amygdaloidal basalts from several lahar deposits; and (4) a subophitic gabbro and a cross-cutting clinopyroxene-phyric dyke from the gabbro unit (Fig. 1B, Tables S1–S2). Although most basalt samples are rel-

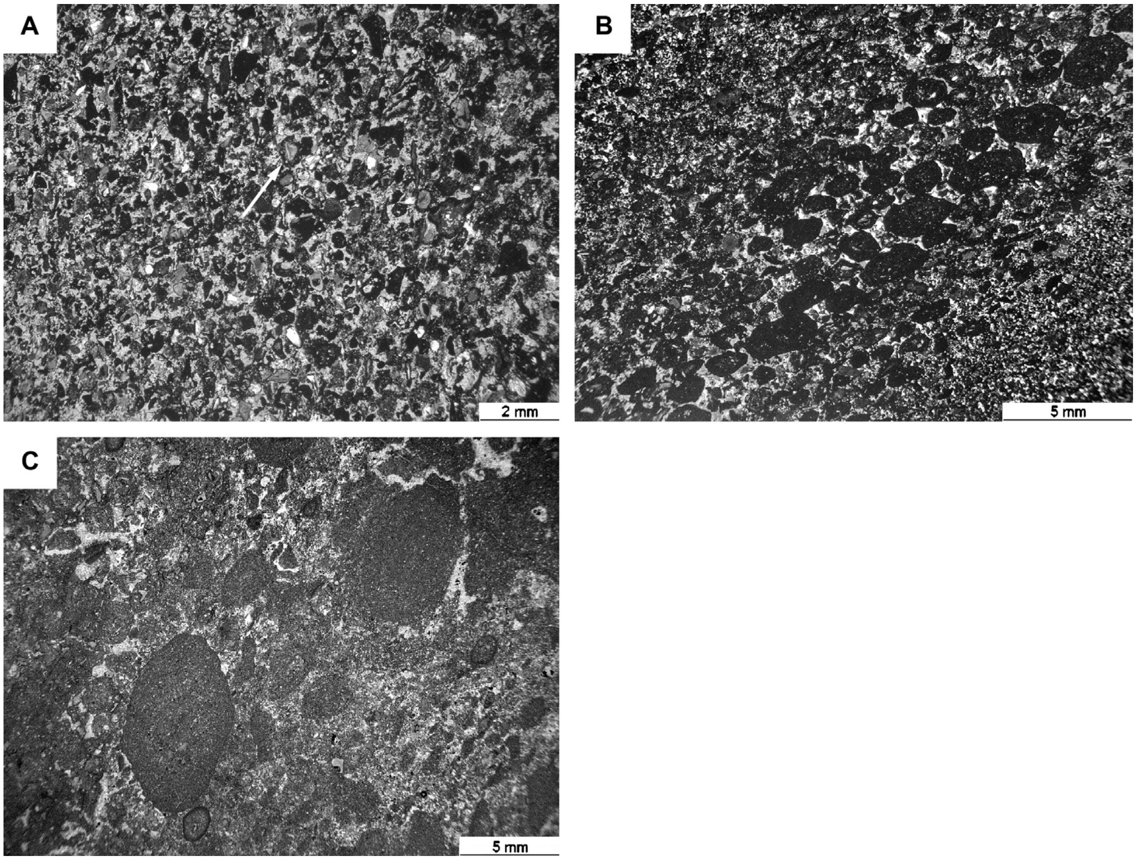

Fig. 4. Thin section images of coarse lapilli tuffs from the volcaniclastic unit. **A)** Tuff DB15-066 with. The white arrow points at an armoured lapilli. **B)** Graded tuff DB15-068 with deformed accretionary lapilli. **C)** Tuff DB15-080 with large accretionary lapilli.

atively fresh, more intense alteration of the tuffs is suggested by their higher volatile contents (LOI = 4.76–7.70 wt.%) and unusual behaviour of Si, Na and K compared to immobile trace elements (Fig. S1). Therefore, our interpretations are based on elements less susceptible to low temperature alteration (i.e., high field strength and rare earth elements). Consistent behaviour of immobile trace elements (e.g., Ti) and Mg# (Mg# = molecular ratio of Mg/[Mg + Fe] × 100) support similar, tholeiitic basalt compositions of the basalts (Mg# = 53–58), tuffs (Mg# = 59–67), and basalt clasts (Mg# = 64–67) (Fig. S1). In contrast, the gabbro and dyke have a more differentiated basaltic andesite composition (Mg# = 42 and 41, respectively). Higher differentiation of the gabbro and dyke relative to our other samples is also consistent with their overall higher immobile trace element contents (Fig. 5).

Immobile trace element contents of samples grouped based on lithological characteristics and field relationships provides valuable insight into the magmatic and tectonic affinities of the accreted sequences (Figs. 5–6). Samples from the basalt units have flat patterns and moderate Th depletion in primitive mantle (PM)-normalised multi-element diagrams (Fig. 5A). This pattern closely resembles that of oceanic plateau basalts and some associated intrusions elsewhere in the Western Cordillera (Villagómez et al., 2011; Rodríguez and Arango, 2013; Fig. 5A). Significantly, a similar plateau affinity is observed in the tuffs and basalt clasts of the volcaniclastic unit (Figs. 5B–C). Close compositional similarity of samples from the basalt and volcaniclastic units is also illustrated in a selection of trace element variation diagrams, which additionally show that these rocks do not have MORB-like geochemical signature and closely resemble some of the magma types produced during emergence of the Ontong Java Plateau (Fitton and Godard, 2004) (Figs. 5F and 6). Overall this provides compelling support for the origin of the volcaniclastic unit in an oceanic plateau setting.

Tuff sample DB15-062 is a notable exception to the occurrence of plateau-related tuff and basalt clasts in the volcaniclastic unit. This sample has clear arc affinity characterised by progressive enrichment in the most incompatible trace elements (i.e., LREE and Th) and lower Nb content than that of oceanic plateau rocks (Figs. 5B–6). This sample is compositionally very similar to other arc-related igneous rocks recently found in the Barroso formation north and around of the studied area (Rodríguez and Arango, 2013; Fig. 5B). Significantly, sample DB15-062 was collected from an interval of finer tuff that also includes plateau-like tuff DB15-063 (Fig. 3B). This clearly indicates coeval plateau and arc volcanism at the time of formation of the volcaniclastic sequences.

Gabbro sample JB17-130 has a plateau geochemical signature similar to the basalt units (Figs. 5D–6) thus supporting a similar origin for these sequences. Higher incompatible trace element contents and lower Mg# of the gabbro relative to the basalts is consistent with the gabbro being more differentiated. A plateau origin of the gabbro is in good agreement with previous regional observations that indicate that gabbros and dolerites are a common component of the Caribbean plateau in large parts of the Western Cordillera (Kerr et al., 1997; Villagómez et al., 2011). However, other samples from the gabbro unit in the studied area (Zapata-Villada et al., 2017) have slightly distinct geochemical characteristics, with lower trace element contents (Fig. 5D) and variable Th enrichments relative to Nb (Figs. 5–6). These characteristics are discussed below with the tectonic context of formation of the studied sequences.

Finally, the andesite dyke that crosscuts the gabbro unit has typical arc geochemical affinities, with a progressive enrichment of incompatible trace elements and Nb–Ti negative anomalies on

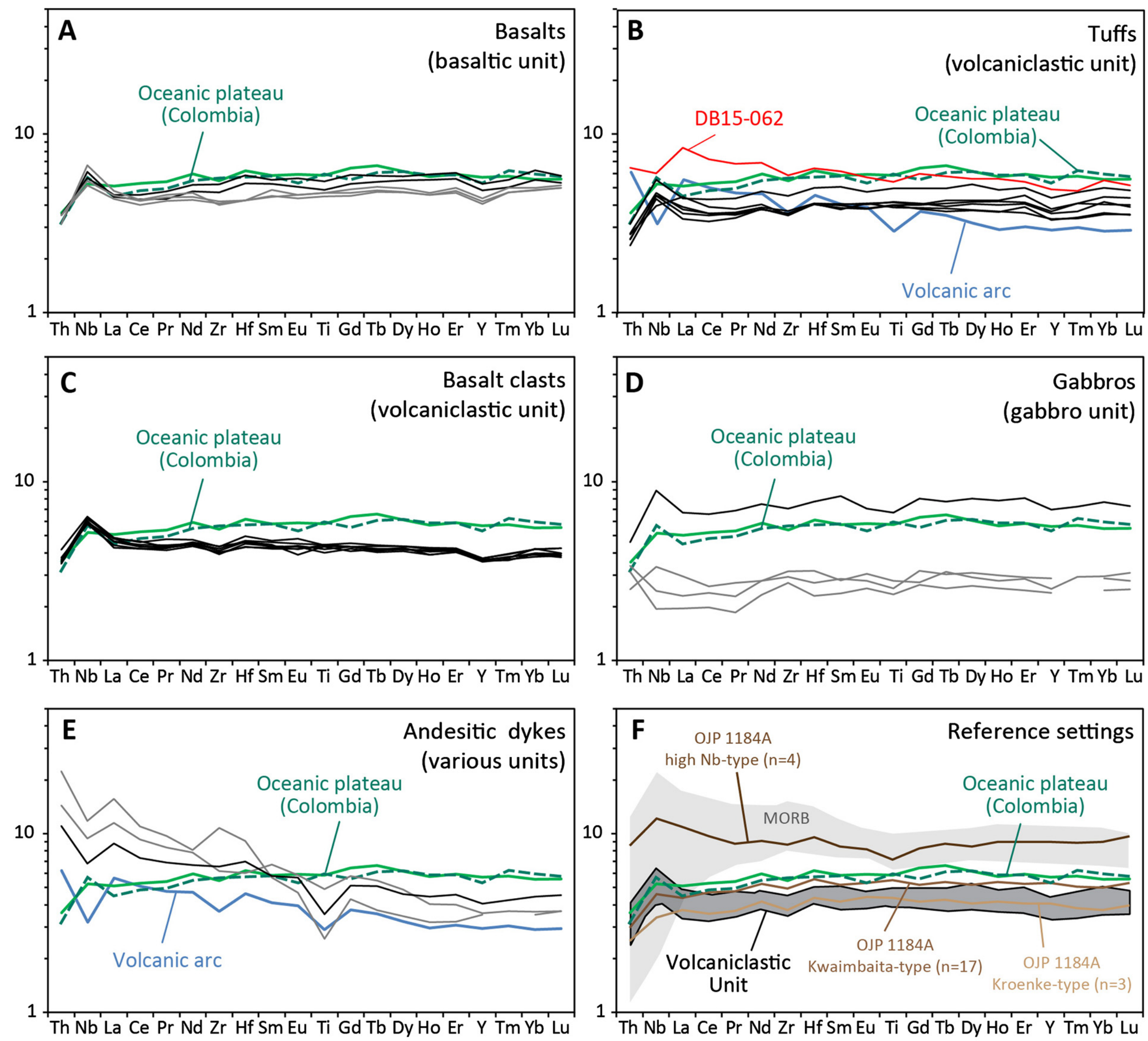

Fig. 5. Primitive mantle-normalised multi-elementary diagrams of whole rock samples. Results from Zapata-Villada et al. (2017) are shown in grey. Colombian oceanic plateau references are based on an average of oceanic plateau lavas, dolerites and gabbros from the Western Cordillera from Villagómez et al. (2011) (dashed green line, $n = 9$) and from Rodríguez and Arango (2013) (continuous green line, $n = 21$). Volcanic arc reference is based on an average of basalts to andesites ($n = 22$) from the northern Western Cordillera (Rodríguez and Arango, 2013). Reference datasets in (F) include averages of magma types found in the Ontong Java plateau (OJP) at ODP Site 1184A that contains subaerial volcaniclastic deposits (Fitton and Godard, 2004). N- to E-MORB compositional range is based on 13 samples from segment 9°30′N of the East Pacific Rise (Waters et al., 2011).

a normalised multi-element diagram (Figs. 5E–6). Two andesitic dykes from other units in the studied area (Zapata-Villada et al., 2017) have similar arc geochemical affinities. However, unlike tuff sample DB15-062, the andesitic dykes have trace element contents distinct from to those of other volcanic arc igneous rocks of the Barroso formation (Fig. 5E). These geochemical constraints and the occurrence of the dykes in different accreted units suggest that they represent younger volcanic activity in the subduction zone following accretion of the plateau sequences and, possibly, other arc sequences recently recognised in the northern Western Cordillera (Rodríguez and Arango, 2013; Weber et al., 2015). However, characterising the exact origin and age of this post-accretion volcanic activity is beyond the scope of this study.

4.3. *Clinopyroxene geochemistry*

In order to further assess the origin of tuffs from the volcaniclastic unit we analysed clinopyroxene in 3 samples of fine to coarse tuff, including accretionary lapilli, which we compared to those in (i) a coarse-grained oceanic plateau basalt from the eastern basalt unit and (ii) our arc-related andesitic dyke from the gabbro unit. Tuff sample DB15-062 that occurs in the volcaniclastic sequence but has a volcanic arc geochemical signature was not included for comparison due to lack of clinopyroxene in this sample. Our results show that all analysed clinopyroxenes are augites (Fig. S3), with a median Mg# of 81–83 in the tuffs, 84 in the basalt and 71 in the andesite. These Mg# values are consistent with the euhedral (unresorbed) habit of the analysed minerals, and suggest equilibrium between the clinopyroxenes and their host rock (assuming $K_D(\text{Fe–Mg})^{cpx\text{-}liq}$ of 0.28 ± 0.08 from Putirka, 2008) (Fig. 7A). With the exception of an atypical augite in tuff sample DB15-063, the clinopyroxenes define a very consistent differentiation trend, with a gradual Ti increase with decreasing Mg# (Fig. 7B). Lack of decreasing Ti at lower Mg# indicates that all the clinopyroxene crystallised from relatively undifferentiated melts, without coeval crystallisation of Ti-rich phases (e.g., ilmenite); this means that the Ti content in clinopyroxene in these samples can be used to assess the tectonic setting of formation of the melt

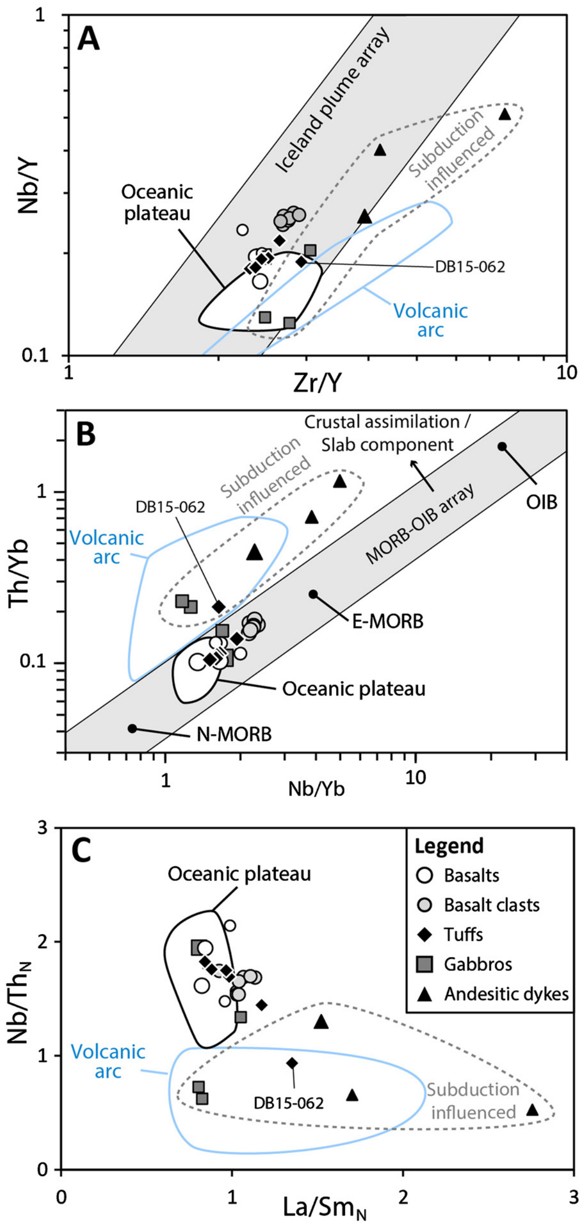

Fig. 6. Whole rock immobile trace element diagrams, with same reference data as in Fig. 5 and additional plateau samples from Kerr et al. (1997) ($n = 26$). Samples from Zapata-Villada et al. (2017) with smaller symbols. **A)** Zr/Y vs Nb/Y diagram with Iceland plume array from Fitton et al. (1997). **B)** Nb/Y vs Th/Yb diagram from Pearce (2008). **C)** La/Sm$_N$ vs Nb/Th$_N$ diagram (N = primitive mantle-normalised).

in which they crystallised (Leterrier et al., 1982). In Ca+Na vs Ti and Ca vs Ti+Cr discrimination diagrams of Leterrier et al. (1982), clinopyroxenes from the tuff samples have a MORB-like affinity with relatively high Ti+Cr at a given Ca content (Fig. 7C–D). These characteristics are indistinguishable from those of clinopyroxene in the oceanic plateau basalt. In contrast, clinopyroxene in the arc-related andesitic dyke have a supra-subduction affinity with lower Ti+Cr at a given Ca content. These observations are consistent with the whole rock geochemical results and confirm an oceanic plateau origin of the bulk of the volcaniclastic unit. In addition, consistency of clinopyroxene compositions in the basalt and tuffs indicate that they formed in a magmatic system with little mixing/mingling of compositionally contrasted melts.

5. Discussion

5.1. Evidence for emergence of the Caribbean plateau

The Western Cordillera of Colombia is generally considered to expose fragments of the Caribbean plateau that formed in the Pacific Ocean ca. 90 Ma before accreting along northern South America in the Late Cretaceous (e.g., Kerr et al., 1997; Kennan and Pindell, 2009; Villagómez et al., 2011). It was also proposed that oceanic sequences accreted in the Western Cordillera provide a valuable opportunity to reconstruct the stratigraphy of an accreted oceanic plateau (Kerr et al., 1998). Several lines of evidence from recent regional work and this study support these hypotheses. First, although parts of the northern Western Cordillera have a supra-subduction origin (Rodríguez and Arango, 2013; Weber et al., 2015), regional geochemical constraints clearly support an oceanic plateau origin for most of the rocks in the studied area and the southern Western Cordillera (Kerr et al., 1997; Villagómez et al., 2011; Rodríguez and Arango, 2013; Zapata-Villada et al., 2017; this study). Second, geochronological constraints in the studied area and southern Western Cordillera suggest a similar ca. 90 Ma age of formation of oceanic plateau basalts and gabbros (Villagómez et al., 2011; Zapata-Villada et al., 2017). This is consistent with their formation during the same volcanic phase of the Caribbean plateau. Finally, hemipelagic to pelagic sedimentary deposits that can form a significant part of the Western Cordillera (e.g., Moreno-Sanchez and Pardo-Trujillo, 2003) do not occur between fault-bounded igneous units in the studied area. This type of lithostratigraphic relationship is distinct from that of highly composite accretionary complexes that form through long-term stacking of originally dispersed portions of the ocean floor (e.g., Kusky et al., 2013). Instead, lithostratigraphic relations in the studied area closely resemble those produced by the accretion of large fragments of seamounts or thickened oceanic crust during discrete collisional events at shallow depth in the subduction zone (e.g., Buchs et al., 2011; Schnur and Gilbert, 2012). Therefore, the studied accreted sequences offer a valuable opportunity to characterise the volcanic evolution of an exposed portion of the Caribbean plateau.

Three main modes of formation are preserved in the studied Caribbean plateau sequences: (1) submarine volcanic activity associated with the emplacement of pillow lavas in the basalt units; (2) subvolcanic intrusion(s) documented by the gabbro unit; and (3) volcano-sedimentary processes associated with the formation of the volcaniclastic unit (Fig. 1B). Lack of detrital deposits in the basalt units suggests that they represent an early, pre-emergence phase of the oceanic plateau, because post-emergence volcanic sequences in oceanic island settings typically include abundant *in situ* or reworked subaerial deposits (e.g., Garcia et al., 2007; Buchs et al., 2018) that have not been observed in the studied area. In contrast, the volcaniclastic unit that includes fine to coarse lapilli tuffs with accretionary lapilli and interbedded debris flow/lahar deposits with rounded basalt clasts represent a later, post-emergence stage of the oceanic plateau.

Layered fallout tuffs with accretionary and armoured lapilli are abundant in the studied volcaniclastic unit. These tuffs are very similar to those described at ODP Site 1184 on the Ontong Java Plateau, where they are considered to record several phreatomagmatic eruptions during the main volcanic phase of this oceanic plateau (Thordarson, 2004). The tuffs in the studied area have an oceanic plateau geochemical signature similar to other accreted igneous sequences of the western Cordillera in Colombia as well as some of the volcaniclastic deposits at ODP Site 1184 on the Ontong Java Plateau (Fig. 5F). These volcanic and geochemical observations support a phase of phreatomagmatism similar to that of the Ontong Java Plateau during and/or after syn-volcanic emergence of the Caribbean plateau. Low volatile contents that are gener-

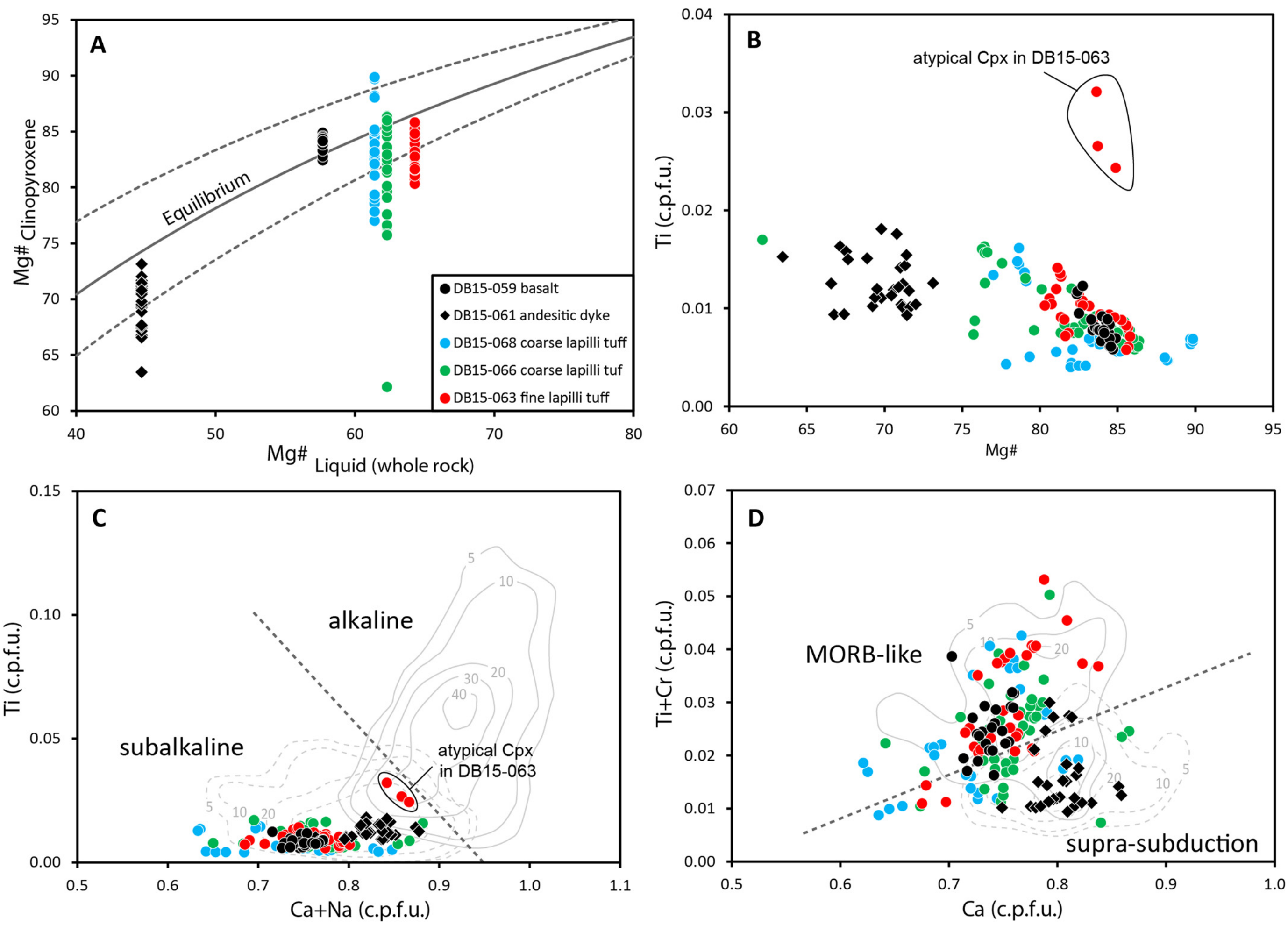

Fig. 7. Geochemical composition of clinopyroxenes from 3 tuff samples, plateau basalt DB15-059 and arc-related andesitic dyke DB15-061. **A)** Rhodes diagram with calculated equilibrium curve between clinopyroxenes and their theoretical host melt, assuming $K_D(\mathrm{Fe–Mg})^{cpx\text{-}liq}$ of 0.28 ± 0.08 (Putirka, 2008). **B)** Mg# vs Ti diagram. **C** and **D)** Ca+Na vs Ti, and Ca vs Ti+Cr diagrams with discrimination boundaries from Leterrier et al. (1982).

ally observed in oceanic plateau magmas (Roberge et al., 2004; Kamenetsky et al., 2010) suggest that magma fragmentation was driven by interaction of the magma with non-magmatic water during phreatomagmatic eruptions, as commonly associated with the formation of accretionary lapilli (Brown et al., 2012). However, it remains unclear whether the studied lapilli reflect fragmentation due to interaction of magma with sea, lake or ground water. In any case, proximal tuff layers with cm-sized accretionary lapilli are interbedded with debris flow/lahar deposits that clearly document subaerial reworking of basaltic material. Therefore, this indicates a complex interplay of volcanic and erosional processes in an oceanic island setting.

The occurrence of large rounded clasts of amygdaloidal basalts with an oceanic plateau composition is a significant observation that suggests that the Caribbean plateau had already undergone a phase of uplift and erosion at the time of the observed phreatomagmatic activity. This emergence could have been induced by mantle plume dynamics, tectonic processes and/or inflation by subvolcanic intrusions (as for example, recorded by the gabbro unit) rather than eruptive processes only. Volcanic inflation is a mechanism that can contribute to emergence of oceanic islands in the Atlantic (e.g., Ramalho et al., 2015). Our field work and previous observations of abundant sills in accreted sequences of the Caribbean plateau in Colombia (Kerr et al., 1998) suggest that inflation could also play a role during the emergence of oceanic plateaus.

5.2. Palaeogeographic evolution of the Caribbean Large Igneous Province in the Late Cretaceous

Most tectonic reconstructions of the Caribbean suggest that the Caribbean plateau formed in the Pacific ca. 90 Ma, possibly above the starting plume head of the Galapagos Hotspot, before being tectonically incorporated between the Americas in the Late Cretaceous and Cenozoic (e.g., Duncan and Hargraves, 1984; Burke, 1988; Hoernle et al., 2004; Pindell and Kennan, 2009; Wright and Wyld, 2011; Neill et al., 2011). As explained above this interpretation is consistent with geological constraints from the Western Cordillera in Colombia. This interpretation is also in good agreement with the age, tectono-stratigraphic relations and spatial distribution of Cretaceous volcanic arc remnants and metamorphic complexes that are exposed today around the Caribbean Plate (Fig. 1A). These remnants preserve clear evidence for the occurrence of intra-oceanic subduction zones that could have facilitated the movement of the Caribbean plateau between the Americas (Neill et al., 2011; Pindell et al., 2011; Wright and Wyld, 2011; Jaramillo et al., 2017). Although it is tempting to assume that a single volcanic arc developed around the early Caribbean plateau (Whattam and Stern, 2015), regional geological constraints, in particular in Colombia, indicate that distinct subduction zones developed at different times and places around this plateau (Wright and Wyld, 2011; Jaramillo et al., 2017).

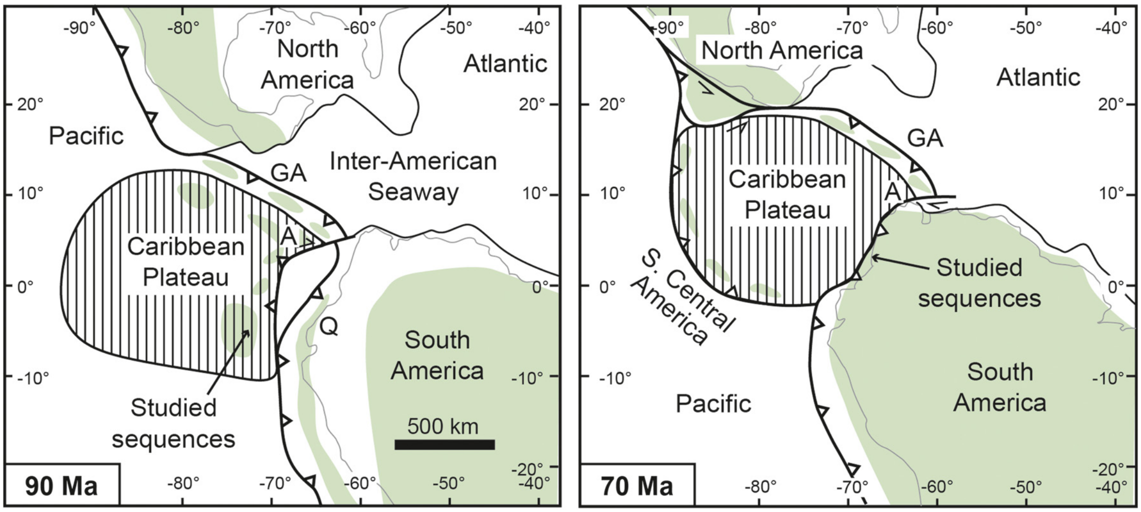

Fig. 8. Tectonic model of the inter-American seaway in the Late Cretaceous (modified from Pindell and Kennan, 2009, with key elements of Wright and Wyld, 2011 and Jaramillo et al., 2017 for the southern Caribbean and northern South America). Possible land exposures are shown in green. GA: Greater Antilles arc; A: Aruba Island part of the Colombian-Leeward Antilles arc (Wright and Wyld, 2011); Q: Quebradagrande complex.

In our preferred tectonic reconstruction (Fig. 8), Early to Late Cretaceous subduction zones developed along and/or close to the eastern to southern margins of the Caribbean plateau, and are preserved today as arc remnants in the eastern Caribbean (Burke, 1988; Wright and Wyld, 2011; Pindell et al., 2011). One of these subduction zones is documented by supra-subduction igneous rocks that overly and intruded Caribbean plateau sequences exposed on Aruba Island (Wright and Wyld, 2011). This zone could also include Mesozoic supra-subduction sequences recently discovered in the northern Western Cordillera of Colombia (Rodríguez and Arango, 2013; Weber et al., 2015). This interpretation is in agreement with our results that document a fine tuff that is interbedded with oceanic plateau sequences and has supra-subduction geochemical affinities similar to those of volcanic arc remnants in the northern Western Cordillera (sample DB15-062, Fig. 5B). In addition, lower trace element contents and variable Th enrichments relative to Nb of some gabbros in the studied area (Figs. 5–6), may represent small influence of a possible slab component. This component could reflect minor influence of a west-facing subduction zone during the formation of the south-eastern margin of the Caribbean plateau, before its accretion in the Late Cretaceous (Fig. 8). In contrast, the Quebradagrande Complex in Colombia documents a distinct, Early to Late Cretaceous subduction zone that developed along South America (Nivia et al., 2006; Villagómez and Spikings, 2013; Spikings et al., 2015; Jaramillo et al., 2017). Finally, a more recent subduction zone initiated along the Caribbean plateau in south Central America in the latest Cretaceous possibly due to collision of the Caribbean plateau with South America (Buchs et al., 2010; Wegner et al., 2011). In this regional tectonic interpretation, the Caribbean plateau formed a volcanic promontory between the Americas in the Late Cretaceous (Fig. 8).

Current regional constraints allow minor variations in the tectonic evolution of the Caribbean plateau. In particular, an earlier formation of the plateau is suggested by rare Early Cretaceous to Jurassic (?) geochronological ages in the circum-Caribbean area (Hoernle et al., 2004; Rodríguez and Arango, 2013) and a ca. 100 Ma supra-subduction tonalite that cross-cuts oceanic plateau sequences in the northern Western Cordillera (Weber et al., 2015). Significantly, these variations are also consistent with an inter-American location of the Caribbean plateau in the Late Cretaceous.

Volcaniclastic deposits from the Western Cordillera clearly support local emergence of the Caribbean plateau in the Late Cretaceous. Interestingly, tuff deposits with accretionary lapilli similar to those described in this study may also occur on Aruba Island (Fig. 1). The Aruba tuffs are part of an Upper Cretaceous volcaniclastic unit that occurs on top of an erosional unconformity with basaltic conglomerates, above pillow basalts with an oceanic plateau geochemical composition (White et al., 1999; Wright and Wyld, 2011). A geochemical analysis of a tuff sample in the volcaniclastic unit is consistent with a plateau origin (sample ARU 96–112; White et al., 1999). Although the relation of this sample to the sequences of underlying (?) conglomerate and pillow lava is unknown, the tuff sequence on Aruba could possibly represent an analogue of the studied sequences in Colombia. This would indicate widespread emergence of the western edge of the Caribbean plateau in the Late Cretaceous.

5.3. Palaeo-environmental implications

As indicated above, before this study there was very limited evidence of emergent volcanic activity associated with the later stages of formation of the Caribbean plateau. However, the likely close proximity of an emergent plateau with subaerial and shallow-water volcanism, to the Pacific entrance of the Inter-American seaway ca. 90 Ma (e.g., Pindell and Kennan, 2009) has several significant environmental implications.

Firstly, the opening of the Inter-American seaway/proto-Caribbean, commencing in the Jurassic (Pindell and Kennan, 2009) would have led to an evolutionary divergence in flora and fauna between North and South America (McIntyre et al., 2017). However, since the Cretaceous several island arc-derived landbridges, or chains of islands separated by shallow water, have been suggested on the basis of evolutionary patterns and molecular phylogenies (e.g. Iturralde and MacPhee, 1999; Pennington and Dick, 2004; Chakrabarty, 2006; Woodburne, 2010). As noted by Iturralde and MacPhee (1999) the evidence for links between North and South America becomes much less certain before the mid-Cenozoic, due to a lack of geological data. The evidence for subaerial volcanism on the Caribbean plateau, ca. 90 Ma, raises the possibility of a landbridge and relatively shallow water between the Americas that may have facilitated species migration (Gayet et al., 1992; McCarthy, 2005).

Secondly, as noted by Kerr (1998, 2005) a significant shallowing of the sea at the Pacific entrance to the proto-Caribbean, would have restricted the movement of oxygenated bottom water from the Pacific to the juvenile Atlantic. This would have contributed to the major global oceanic anoxia event (OAE-2) and black shales in and around the Atlantic basin at the Cenomanian–Turonian boundary (ca. 94 Ma) (de Boer, 1986; Kerr, 2005). However, although the Cenomanian–Turonian event represents the major phase of oceanic anoxia in the late Cretaceous, the Coniacian–Santonian interval (90–84 Ma) is also marked by organic-rich deposits (Jenkins et al., 2002), known as OAE-3. However, OAE-3 is not marked by a single black shale event, but instead anoxic episodes are distributed over a longer time period and occur in different basins at different times (Wagreich, 2012). Interestingly, OAE-3 black shale occurrences are restricted to the equatorial to mid-latitudinal Atlantic and adjacent basins such as parts of the Caribbean (Wagreich, 2012). This restricted geographic distribution and temporally spread nature of the OAE-3 event is consistent with a prolonged period (of at least up to 7 m.y.) of restricted flow of deep oxygenated Pacific seawater into the Atlantic, due to the extensive shallow water and subaerial eruption of a substantial portion of the Caribbean plateau. In addition, accreted fragments of the Caribbean plateau are tectonically associated with Upper Cretaceous black cherts of the Penderisco formation in the Western Cordillera of Colombia (Rodríguez et al., 2013; Pardo-Trujillo, 2018). Although more work is needed to determine the exact age and origin of the cherts, these sequences also suggest a causal link between the emplacement of the Caribbean plateau and regional anoxic events in the Late Cretaceous.

6. Conclusions

Accreted oceanic sequences in the western Cordillera of Colombia reveal that the Caribbean oceanic plateau experienced a phase of subaerial volcanic activity in the Late Cretaceous (ca. 90 Ma). An interplay of phreatomagmatic eruptions and subaerial erosional processes during the formation of island(s) on top of the plateau is well documented by layered tuffs with accretionary lapilli and interbedded lahar deposits with rounded clasts of basalt. These deposits and their clinopyroxene content have an oceanic plateau geochemical signature similar to that of submarine lavas and intrusive rocks that form most of the Caribbean plateau. This suggests that the island(s) formed during a continuous phase of magmatism with transition from submarine to subaerial conditions. These results complement stratigraphic, volcanologic and geochemical constraints from oceanic plateaus previously drilled in the Pacific (e.g., Thordarson, 2004; Yasuhara et al., 2017), and suggest that these volcanoes experienced a phase of subaerial volcanism. Therefore, similarly to large igneous provinces formed in intra-continental settings, oceanic plateaus should also be regarded as a potential source of rapid release of large volumes of magmatic gases and aerosols in the atmosphere.

Processes that could have contributed to the emergence of the Caribbean plateau include volcanic construction, magmatic intrusions and inflation, and uplift due to mantle plume dynamics. The occurrence of an arc-derived tuff interbedded within subaerial tuffs of the plateau also suggests that emergence could have benefited from tectonic interaction with a nearby subduction zone, before collision of the plateau with South America and development of the south Central American arc. In any case, emergence of the Caribbean plateau most likely contributed to significant obstruction of the inter-American seaway in the Late Cretaceous. Shallowing of the seaway could have triggered drastic reduction of the flow of Pacific oxygenated bottom waters into the juvenile Atlantic, and so likely promoted anoxic events in the Atlantic basin in the Coniacian–Santonian (OAE-3 event). In addition, the emergence of the Caribbean plateau and its interaction with subduction zones during its migration between the Americas provide new support for the development of strings of islands that could have facilitated inter-American migration of terrestrial organisms as early as the Late Cretaceous.

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Appendix A. Supplementary material

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.epsl.2018.07.020.

References

Bourgois, J., Toussaint, J.-F., Gonzalez, H., Azema, J., Calle, B., Desmet, A., Murcia, L.A., Acevedo, A.P., Parra, E., Tournon, J., 1987. Geological history of the Cretaceous ophiolitic complexes of northwestern South America (Colombian Andes). Tectonophysics 143, 307–327.

Brown, R.J., Bonadonna, C., Durant, A.J., 2012. A review of volcanic ash aggregation. Phys. Chem. Earth Parts A/B/C 45–46, 65–78.

Buchs, D.M., Arculus, R.J., Baumgartner, P.O., Baumgartner-Mora, C., Ulianov, A., 2010. Late Cretaceous arc development on the SW margin of the Caribbean Plate: insights from the Golfito, Costa Rica, and Azuero, Panama, complexes. Geochem. Geophys. Geosyst. 11, Q07S24.

Buchs, D.M., Arculus, R.J., Baumgartner, P.O., Ulianov, A., 2011. Oceanic intraplate volcanoes exposed: example from seamounts accreted in Panama. Geology 39, 335–338.

Buchs, D.M., Williams, R., Sano, S., Wright, V.P., 2018. Non-Hawaiian lithostratigraphy of Louisville seamounts and the formation of high-latitude oceanic islands and guyots. J. Volcanol. Geotherm. Res. 356, 1–23. https://doi.org/10.1016/j.jvolgeores.2017.12.019.

Burke, K., 1988. Tectonic evolution of the Caribbean. Annu. Rev. Earth Planet. Sci. 16, 201–230.

Chakrabarty, P., 2006. Systematics and historical biogeography of Greater Antillean Cichlidae. Mol. Phylogenet. Evol. 39, 619–627.

de Boer, P.L., 1986. Changes in the organic carbon burial during the Early Cretaceous. In: Summerhayes, C.P., Shackleton, N.J. (Eds.), North Atlantic Palaeoceanography. In: Geol. Soc. (Lond.) Spec. Publ., pp. 321–331.

Duncan, R.A., Hargraves, R.B., 1984. Plate tectonic evolution of the Caribbean region in the mantle reference frame. Mem. Geol. Soc. Amer. 162, 81–94.

Eldhom, O., Coffin, M., 2000. Large Igneous Provinces and plate tectonics. In: The History and Dynamics of Global Plate Motions. In: Geophys. Monogr., vol. 121, pp. 309–326.

Fitton, J.G., Saunders, A.D., Norry, M.J., Hardarson, B.S., Taylor, R.N., 1997. Thermal and chemical structure of the Iceland plume. Earth Planet. Sci. Lett. 153, 197–208.

Fitton, J.G., Godard, M., 2004. Origin and evolution of magmas on the Ontong Java Plateau. In: Fitton, J.G., Mahoney, J.J., Wallace, P.J., Saunders, A.S. (Eds.), Origin and Evolution of the Ontong Java Plateau. In: Geol. Soc. (Lond.) Spec. Publ., vol. 229, pp. 151–178.

Furnes, H., Fridleifsson, I.B., 1979. Pillow block breccia-occurrences and mode of formation. Neues Jahrb. Mineral. Geol. Palaeontol. 3, 147–154.

Garcia, M.O., Haskins, E.H., Stolper, E.M., Baker, M., 2007. Stratigraphy of the Hawai'i scientific drilling project core (HSDP2): anatomy of a Hawaiian shield volcano. Geochem. Geophys. Geosyst. 8, Q02G20.

Gayet, M., Rage, J.C., Sempere, T., Gagnier, P.Y., 1992. Mode of interchanges of continental vertebrates between North and South-America during the Late Cretaceous and Paleocene. Bull. Soc. Géol. Fr. 163, 781–791.

Hall, R.V., Alvarez, J., Rico, H., 1972. Geología de parte de los departamentos de Antioquia y Caldas (sub-zona II-A): ingeominas. Bol. Geol. XX (1), 1–85.

Hoernle, K., Hauff, F., van den Bogaard, P., 2004. 70 m.y. history (139–69 Ma) for the Caribbean large igneous province. Geology 32, 697–700.
Iturralde-Vinent, M.A., MacPhee, R.D.E., 1999. Paleogeography of the Caribbean region: implications for Cenozoic biogeography. Bull. Am. Mus. Nat. Hist., 1–95.
Jaramillo, J.S., Cardona, A., León, S., Valencia, V., Vinasco, C., 2017. Geochemistry and geochronology from Cretaceous magmatic and sedimentary rocks at 6°35′N, western flank of the Central Cordillera (Colombian Andes): magmatic record of arc growth and collision. J. South Am. Earth Sci. 76, 460–481.
Jenkins, R.B., Landenberger, B., Collins, W.J., 2002. Late Palaeozoic retreating and advancing subduction boundary in the New England Fold Belt, New South Wales. Aust. J. Earth Sci. 49, 467–489.
Kamenetsky, V.S., Gurenko, A.A., Kerr, A.C., 2010. Composition and temperature of komatiite melts from Gorgona Island, Colombia, constrained from olivine-hosted melt inclusions. Geology 38, 1003–1006.
Kennan, L., Pindell, J., 2009. Dextral shear, terrane accretion and basin formation in the Northern Andes: explained only by interaction with a Pacific-derived Caribbean Plate. In: James, K.H., Lorente, M.A., Pindell, J. (Eds.), The Origin and Evolution of the Caribbean Plate. In: Geol. Soc. (Lond.) Spec. Publ., vol. 328, pp. 487–531.
Kerr, A.C., 1998. Oceanic plateau formation: a cause of mass extinction and black shale deposition around the Cenomanian–Turonian boundary? J. Geol. Soc. 155, 619–626.
Kerr, A.C., 2005. Oceanic LIPs: the kiss of death. Elements 1, 289–292.
Kerr, A.C., 2014. Oceanic plateaus. In: Turekian, K.K., Holland, H.D. (Eds.), Treatise on Geochemistry, second edition. Elsevier, Oxford, pp. 631–667.
Kerr, A.C., Marriner, G.F., Tarney, J., Nivia, A., Saunders, A.D., Thirlwall, M.F., Sinton, C.W., 1997. Cretaceous basaltic terranes in western Colombia: elemental, chronological and Sr–Nd isotopic constraints on petrogenesis. J. Petrol. 38, 677–702.
Kerr, A.C., Tarney, J., Nivia, A., Marriner, G.F., Saunders, A.D., 1998. The internal structure of oceanic plateaus: inferences from obducted Cretaceous terranes in western Colombia and the Caribbean. Tectonophysics 292, 173–188.
Kerr, A.C., Tarney, J., Kempton, P.D., Pringle, M., Nivia, A., 2004. Mafic Pegmatites Intruding Oceanic Plateau Gabbros and Ultramafic Cumulates from Bolívar, Colombia: evidence for a ‘Wet’ mantle plume? J. Petrol. 45, 1877–1906.
Kuroda, J., Ogawa, N.O., Tanimizu, M., Coffin, M.F., Tokuyama, H., Kitazato, H., Ohkouchi, N., 2007. Contemporaneous massive subaerial volcanism and late cretaceous Oceanic Anoxic Event 2. Earth Planet. Sci. Lett. 256, 211–223.
Kusky, T.M., Windley, B.F., Safonova, I., Wakita, K., Wakabayashi, J., Polat, A., Santosh, M., 2013. Recognition of ocean plate stratigraphy in accretionary orogens through Earth history: a record of 3.8 billion years of sea floor spreading, subduction, and accretion. Gondwana Res. 24, 501–547.
Leterrier, J., Maury, R., Thonon, P., Girard, D., Marchal, M., 1982. Clinopyroxene composition as a method of identification of the magmatic affinities of paleovolcanic series. Earth Planet. Sci. Lett. 59, 139–154.
McCarthy, D., 2005. Biogeographical and geological evidence for a smaller, completely-enclosed Pacific Basin in the Late Cretaceous. J. Biogeogr. 32, 2161–2177.
McIntyre, S.R.N., Lineweaver, C.H., Groves, C.P., Chopra, A., 2017. Global biogeography since Pangaea. Proc. R. Soc. Lond. B, Biol. Sci. 284.
Moreno-Sanchez, M., Pardo-Trujillo, A., 2003. Stratigraphical and sedimentological constraints on western Colombia: implications on the evolution of the Caribbean plate. In: Bartolini, C., Buffler, R.T., Blickwede, J. (Eds.), The Circum-Gulf of Mexico and the Caribbean: Hydrocarbon Habitats, Basin Formation, and Plate Tectonics, pp. 891–924.
Neill, I., Kerr, A.C., Hastie, A.R., Stanek, K.-P., Millar, I.L., 2011. Origin of the Aves Ridge and Dutch–Venezuelan Antilles: interaction of the Cretaceous Great Arc and Caribbean–Colombian Oceanic Plateau? J. Geol. Soc. 168, 333–348.
Nivia, A., Marriner, G.F., Kerr, A.C., Tarney, J., 2006. The Quebradagrande Complex: a lower cretaceous ensialic marginal basin in the Central Cordillera of the Colombian Andes. J. South Am. Earth Sci. 21, 423–436.
Pardo-Trujillo, A., 2018. Personal communication.
Paton, C., Hellstrom, J., Paul, B., Woodhead, J., Hergt, J., 2011. Iolite: freeware for the visualisation and processing of mass spectrometric data. J. Anal. At. Spectrom. 26, 2508–2518. https://doi.org/10.1039/C1JA10172B.
Pearce, J.A., 2008. Geochemical fingerprinting of oceanic basalts with applications to ophiolite classification and the search for Archean oceanic crust. Lithos 100, 14–48.
Pennington, R.T., Dick, C.W., 2004. The role of immigrants in the assembly of the South American rainforest tree flora. Philos. Trans. R. Soc. Lond. B, Biol. Sci. 359, 1611–1622.
Pindell, J., Kennan, L., 2009. Tectonic evolution of the Gulf of Mexico, Caribbean and northern South America in the mantle reference frame: an update. In: James, K., Lorente, M.A., Pindell, J. (Eds.), Spec. Publ. - Geol. Soc. Lond., vol. 328, pp. 1–55.
Pindell, J., Maresch, W.V., Martens, U., Stanek, K., 2011. The Greater Antillean Arc: Early Cretaceous origin and proposed relationship to Central American subduction mélanges: implications for models of Caribbean evolution. Int. Geol. Rev., 1–13.
Putirka, K.D., 2008. Thermometers and barometers for volcanic systems. Rev. Mineral. Geochem. 69, 61–120.
Ramalho, R.S., Brum da Silveira, A., Fonseca, P.E., Madeira, J., Cosca, M., Cachão, M., Fonseca, M.M., Prada, S.N., 2015. The emergence of volcanic oceanic islands on a slow-moving plate: the example of Madeira Island, NE Atlantic. Geochem. Geophys. Geosyst. 16, 522–537.
Roberge, J., White, R.V., Wallace, P.J., 2004. Volatiles in submarine basaltic glasses from the Ontong Java Plateau (ODP Leg 192): implications for magmatic processes and source region compositions. In: Geol. Soc. (Lond.) Spec. Publ., vol. 229, pp. 239–257.
Rodríguez, G., Arango, M.I., 2013. Barroso formation: a theoleiitic volcanic arc and San José de Urama dibases: a T-MORB type accretionary prism in the northern segment of the Western Cordillera of Colombia. Bol. Cienc. Tierra 33, 17–38.
Rodríguez, G., Zapata, G., Gómez, J.F., 2013. Geología de la Plancha 114 Dabeiba. Map of the Servicio Geológico Colombiano.
Schnur, S.R., Gilbert, L.A., 2012. Detailed volcanostratigraphy of an accreted seamount: implications for intraplate seamount formation. Geochem. Geophys. Geosyst. 13, Q0AM05.
Sinton, C.W., Duncan, R.A., 1997. Potential links between ocean plateau volcanism and global ocean anoxia at the Cenomanian–Turonian boundary. Econ. Geol. 92, 836–842.
Skilling, I.P., 2002. Basaltic pahoehoe lava-fed deltas: large-scale characteristics, clast generation, emplacement processes and environmental discrimination. In: Geol. Soc. (Lond.) Spec. Publ., vol. 202, pp. 91–113.
Smith, G.A., Lowe, D.R., 1991. Lahars: volcano-hydrologic events and deposition in the debris flow – hyperconcentrated flow continuum. In: Fisher, R.V., Smith, Gary A. (Eds.), Sedimentation in Volcanic Settings. SEPM Society for Sedimentary Geology, pp. 59–70.
Spikings, R., Cochrane, R., Villagomez, D., Van der Lelij, R., Vallejo, C., Winkler, W., Beate, B., 2015. The geological history of northwestern South America: from Pangaea to the early collision of the Caribbean Large Igneous Province (290–75 Ma). Gondwana Res. 27, 95–139.
Thordarson, T., 2004. Accretionary-lapilli-bearing pyroclastic rocks at ODP Leg 192 Site 1184: a record of subaerial phreatomagmatic eruptions on the Ontong Java Plateau. In: Geol. Soc. (Lond.) Spec. Publ., vol. 229, pp. 275–306.
Villagómez, D., Spikings, R., Magna, T., Kammer, A., Winkler, W., Beltrán, A., 2011. Geochronology, geochemistry and tectonic evolution of the Western and Central Cordilleras of Colombia. Lithos 125, 875–896.
Villagómez, D., Spikings, R., 2013. Thermochronology and tectonics of the Central and Western Cordilleras of Colombia: Early Cretaceous–Tertiary evolution of the Northern Andes. Lithos 160–161, 228–249.
Wagreich, M., 2012. “OAE 3” – regional Atlantic organic carbon burial during the Coniacian–Santonian. Clim. Past 8, 1447–1455.
Waters, C.L., Sims, K.W.W., Perfit, M.R., Blichert-Toft, J., Blusztajn, J., 2011. Perspective on the genesis of E-MORB from chemical and isotopic heterogeneity at 9–10°N East Pacific Rise. J. Petrol. 52, 565–602.
Weber, M., Gómez-Tapias, J., Cardona, A., Duarte, E., Pardo-Trujillo, A., Valencia, V.A., 2015. Geochemistry of the Santa Fé Batholith and Buriticá Tonalite in NW Colombia – evidence of subduction initiation beneath the Colombian Caribbean Plateau. J. South Am. Earth Sci. 62, 257–274.
Wegner, W., Wörner, G., Harmon, R.S., Jicha, B.R., 2011. Magmatic history and evolution of the Central American Land Bridge in Panama since Cretaceous times. Geol. Soc. Am. Bull. 123, 703–724.
Whattam, S.A., Stern, R.J., 2015. Late Cretaceous plume-induced subduction initiation along the southern margin of the Caribbean and NW South America: the first documented example with implications for the onset of plate tectonics. Gondwana Res. 27, 38–63.
White, J.D.L., Houghton, B.F., 2006. Primary volcaniclastic rocks. Geology 34, 677–680. https://doi.org/10.1130/g22346.1.
White, R.V., Tarney, J., Kerr, A.C., Saunders, A.D., Kempton, P.D., Pringle, M.S., Klaver, G.T., 1999. Modification of an oceanic plateau, Aruba, Dutch Caribbean: implications for the generation of continental crust. Lithos 46, 43–68.
Woodburne, M.O., 2010. The Great American biotic interchange: dispersals, tectonics, climate, sea level and holding pens. J. Mamm. Evol. 17, 245–264.
Wright, J.E., Wyld, S.J., 2011. Late Cretaceous subduction initiation on the eastern margin of the Caribbean–Colombian Oceanic Plateau: one Great Arc of the Caribbean (?). Geosphere 7, 468–493.
Yasuhara, M., Ando, A., Iba, Y., 2017. Past emergent phase of Shatsky Rise deep-marine igneous plateau. Sci. Rep. 7, 15423.
Zapata-Villada, J.P., Restrepo, J.J., Cardona-Molina, A., Martens, U., 2017. Geochemistry and geochronology of the basic volcanic and gabroic rocks in the Altamira region, Western Cordillera of Colombia: a record of overimposed Cretaceous plateau and oceanic arc environments. Bol. Cienc. Tierra 39, 13–30.